BEAMING IN GAMMA-RAY BURSTS: EVIDENCE FOR A STANDARD ENERGY RESERVOIR

D. A. Frail[*], S. R. Kulkarni[† ‡], R. Sari,[§] S. G. Djorgovski[†], J. S. Bloom[†], T. J. Galama[†], D. E. Reichart[†], E. Berger[†], F. A. Harrison[†], P. A. Price[†¶], S. A. Yost[†], A. Diercks[†], R. W. Goodrich[‖], F. Chaffee[‖]

[*] National Radio Astronomy Observatory, P.O. Box 0, Socorro, NM 87801, USA
[†] California Institute of Technology, Palomar Observatory 105-24, Pasadena, CA 91125, USA
[‡] Massachusetts Institute of Technology, Physics Dept., Cambridge, MA 02139, USA
[§] California Institute of Technology, Theoretical Astrophysics 130-33, Pasadena, CA 91125, USA
[¶] School of Astronomy & Astrophysics, Mount Stromlo Observatory, Cotter Road, Weston, ACT, 2611, Australia
[‖] W. M. Keck Observatory, Kamuela, HI 96743, USA

Gamma-ray bursts (GRBs) are the most brilliant objects in the Universe but efforts to estimate the total energy released in the explosion – a crucial physical quantity – have been stymied by their unknown geometry: spheres or cones. We report on a comprehensive analysis of GRB afterglows and derive their conical opening angles. We find that the gamma-ray energy release, corrected for geometry, is narrowly clustered around 5×10^{50} erg. We draw three conclusions. First, the central engines of GRBs release energies that are comparable to ordinary supernovae, suggesting a connection. Second, the wide variation in fluence and luminosity of GRBs is due entirely to a distribution of opening angles. Third, only a small fraction of GRBs are visible to a given observer and the true GRB rate is at least a factor of 500 times larger than the observed rate.

This paper has been submitted to Nature. You are free to use the results here for the purpose of your research. In accordance with the editorial policy of Nature, we request that you not discuss this result in the popular press. If you have any question or need clarifications please contact Dale Frail, dfrail@nrao.edu or Shri Kulkarni, srk@astro.caltech.edu.

Observations of GRBs are well described by the fireball model,[1] in which an explosive flow of relativistic matter (ejecta) is released from a central source. The collision of fast-moving ejecta with slower moving ejecta result in bursts of gamma rays. Shortly thereafter, the ejecta starts shocking and sweeping up significant amounts of circumburst matter. The shocked gas, hereafter called the blast wave, powers long-lived and broad-band (X-ray, optical and radio) emission – the so-called afterglow emission.

The afterglow emission appears to be primarily synchrotron radiation. As with other astrophysical shocks, the shocked electrons are accelerated to relativistic energies, forming a power-law distribution, $dN/dE_e \propto E_e^{-p}$; here, E_e is the energy of the electron and p, the index of the power law. In the presence of magnetic fields, the electrons radiate synchrotron emission with a flux $f(t,\nu) \propto t^{\alpha}\nu^{\beta}$, where the spectral index (β) and the temporal index (α) are related to p and the dynamics of the blast wave.[2] Broad-band observations have repeatedly confirmed the expectations of this simple picture.[3–5]

The two outstanding issues in this field are (a) determining the progenitors of GRBs and (b) understanding the physics of the central engine. The focus of this *Article* is the latter topic, specifically the energetics of these mysterious sources.

Observationally it is known[6] that the fluence (defined as the received energy per unit area) of the broad-band afterglow phase is always (and usually much) smaller than that of the gamma-ray burst fluence. This then motivates the use of the isotropic equivalent gamma-ray energy, $E_{\rm iso}(\gamma) = 4\pi F_\gamma d_L^2 (1+z)^{-1}$ as a surrogate for the energy released by the central engine. Here, F_γ is the fluence of the burst; z is the redshift; and d_L is the luminosity distance.

However, $E_{\rm iso}(\gamma)$ could grossly overstate the true gamma-ray energy release (E_γ) if the explosion is not spherical. Indeed, jets are present in almost all accretion-driven phenomena, e.g., young stellar objects, neutron star binaries, and quasars. Likewise, there is excellent observational evidence for GRB fireballs with conical geometry. Henceforth, following standard usage, we will interchangeably use the term "jet" for conical blast waves.

As a result of relativistic beaming ("abberation"), an observer can see only a limited portion of the blast wave with angular size $\sim \Gamma^{-1}$, where Γ is the bulk Lorentz factor of the blast wave. This relativistic beaming implies that there is no observable distinction between a spherically expanding blast wave and a conical blast wave (whose opening angle we denote by θ_j) until the blast wave has slowed down to $\Gamma < \theta_j^{-1}$. However, gamma-ray emission is expected to occur when Γ is large, $\Gamma \gtrsim 100$, and thus unless the opening angles are very small, $\theta_j < 0.01$, a conical GRB will not light up the full celestial sphere, but only the so-called beaming fraction $f_b = (1 - \cos\theta_j)$; we note that for $\theta_j \lesssim 1$, $f_b \cong \theta_j^2/2$.

There are two consequences of relativistic beaming: (1) the true GRB rate is f_b^{-1} times larger than the observed GRB rate and (2) the true gamma-ray energy released E_γ is smaller than $E_{\rm iso}(\gamma)$ by the same factor, i.e., $E_\gamma = f_b \times E_{\rm iso}(\gamma)$.

In contrast to the situation during the gamma-ray burst phase, during the afterglow phase Γ ranges from ~ 10 hours after a burst to trans-relativistic ($\Gamma \sim 1$) and even non-relativistic values days to months after the burst. Thus at some point during the lifetime of the afterglow Γ falls below θ_j^{-1} which has a clear observational signature. Thus multi-wavelength (X-ray, optical and radio) afterglow observations offer us an elegant way to measure θ_j. Here, we report an extensive analysis of θ_j values for all well-studied GRBs. From these values of θ_j we are able to infer the true γ-ray energy release of the central engines of GRBs.

The organization of the paper is as follows. First we summarize the physics of conical afterglows followed by extraction of θ_j values from afterglow observations. We then find the surprising result that E_γ is tightly clustered around 5×10^{50} erg. We end with a discussion of the ramifications of this result.

Conical Afterglows

The temporal evolution of the afterglow emission is directly related to the dynamics of the blast wave which in turn is influenced both by the circumburst medium and the geometry of the explosion. The afterglow emission from a conical blast wave[7–11] differs from that of a spherical blast wave in two distinct ways. First, the observer will start noticing a deficit of emitting material when $\Gamma < \theta_j^{-1}$. The magnitude of this deficit, relative to that of a spherical fireball, is proportional to the ratio of the area of the emitting surface for a conical blast wave ($\propto \theta_j^2$) to that of a spherically emitting blast wave ($\propto \Gamma^{-2}$). This deficit results in the afterglow emission declining more rapidly, relative to a spherical case, or a "break" in the power law decay, $\Delta\alpha = 3/4$.

The second effect that also becomes important when $\Gamma \lesssim \theta_j^{-1}$ is the spreading of the jet in the lateral dimension.[10,11] The ejecta now encounter more surrounding matter and decelerate faster than in the spherical case. This results in an overall steepening ($\Delta\alpha = 1.2$–1.5) of the afterglow emission. In the case of a laterally spreading jet, the lightcurve evolves with $\alpha \cong p$. We note $p \sim$ 2.2–2.4 appears to fit all well-studied afterglows (e.g., ref. 11, 12). This value is also favored by shock acceleration models.[13]

The first claim of a jet was made for the radio afterglow of GRB 970508, which showed deviations from the predictions of a simple spherical adiabatic model.[8] However, it was the spectacular isotropic energy release[14] of GRB 990123 – approaching the rest mass of a neutron star – which emphasized the possible importance of jets in GRBs. A case for a jet in the afterglow of this burst was made on the basis of a sharp break ($\Delta\alpha \geq 0.7$)[15] in the optical afterglow and upper limits in the radio.[16] The clearest evidence for a jet is a sharp break over a broad range of frequencies and such a signature was seen in the lightcurves of GRB 990510 at optical[17,18] and radio[18] wavelengths and was found to be consistent with the X-ray[19] light curve. Furthermore, the detection of polarization[20,21] from this event gave further credence to the jet hypothesis: the non-spherical geometry leads to polarized signal, from which the geometry of the jet can be inferred.[22,23]

More recently, the identification of jets has shifted from single frequency measurements to global model fitting of joint optical, radio and X-ray datasets (e.g., ref. 5, 24). This approach has the advantage that by simultaneously fitting all the data, the final outcome is less sensitive to deviations in small subsets of the data. In addition, since the character of the achromatic break is different above and below the peak of the synchrotron spectrum,[11] broad-band measurements give more robust determinations of the jet parameters. This approach was crucial in distinguishing the jet break for GRB 000301C[5] whose decaying lightcurves exhibited unusual variability,[25] now attributed to microlensing.[26]

Determination of the Jet Opening Angles

We use the formulation of Sari, Piran & Halpern[11] to convert the measured jet break times t_j to opening angles of the conical blast wave:

$$\theta_j = 0.057\left(\frac{t_j}{1\,\mathrm{day}}\right)^{3/8}\left(\frac{1+z}{2}\right)^{-3/8}\left(\frac{E_{\mathrm{iso}}(\gamma)}{10^{53}\,\mathrm{erg}}\right)^{-1/8}\left(\frac{\eta_\gamma}{0.2}\right)^{1/8}\left(\frac{n}{0.1\,\mathrm{cm}^{-3}}\right)^{1/8}, \tag{1}$$

where η_γ is the efficiency of the fireball in converting the energy in the ejecta into γ rays, and n is the mean circumburst density. In Table 1 we present a complete sample of all GRBs with known redshifts as of December 2000. The determinations of t_j are of varying quality. The best events are those for which it is possible to globally model the broad-band data within the physical framework of the relativistic jet model (e.g., GRB 000301C, GRB 990510). For some bursts t_j is inferred from only one band (e.g., GRB 990705) and in some cases with additional constraints from radio observations (e.g., GRB 990123). Finally, there are some events with only upper (e.g., GRB 991208) or lower limits on t_j (e.g., GRB 971214), for which only upper or lower limits of θ_j can be placed, respectively.

We obtain a range in θ_j corresponding to the wide range in t_j values in Table 1 (from $\lesssim 1$ d to 30 d). The derived jet angles vary from 3° to more than 25° with a strong concentration near 4° (Figure 1). It is reasonable to ask whether the observed distribution in Figure 1 suffers from selection effects. To begin we note that out of the 21 known optical afterglows, the light curves of only two GRBs – GRB 980326 (ref. 27) and GRB 980519 (ref. 28) – show rapid decline implying $t_j \lesssim 1$ d. Likewise, out of a sample of 10 bright X-ray afterglows observed with the BeppoSAX satellite there is no evidence for a significant break within 8 to 48 hours after a burst,[29] suggesting that $t_j \gtrsim 1$ d for these events. If we increase the sample to include the 28 GRBs detected by BeppoSAX for which follow-up searches (typically 8–12 hr after the burst) were made for an X-ray afterglow we find only one unambiguous case where no afterglow was detected (GRB 990217; ref. 30). There are a further six cases where a hitherto uncataloged X-ray source was detected in the GRB error circle. In every case the X-ray source is a plausible afterglow but lacking multi-wavelength confirmation, the afterglow identification remains uncertain, e.g., GRB 970111, ref. 31. From these statistics we conclude that steep decays, $t_j \lesssim 1$ d, and therefore very narrow opening angles, $\theta_j < 3°$, are required for less than ten percent of the BeppoSAX GRB sample.

There is another method to infer the existence of a population of GRBs with extremely narrow opening angles. The beaming fraction during the afterglow phase is $\max(\theta_j^2/2,\ \Gamma^{-2}/2)$. Thus, while narrow-angle GRBs will be rare, their X-ray, optical, and radio afterglows which are emitted at increasingly smaller Γ are accordingly less rare.[7] However the current limits[32,33] of these "burst-less" afterglows do not place further significant constraints on θ_j.

GRBs with large opening angles do not suffer from severe beaming but it is not easy to measure t_j for such bursts. For large t_j the afterglow emission is weak and (at optical wavelengths) the host galaxy starts dominating.[34,35] Thus optical observations and X-ray are unlikely to yield t_j. Fortunately, radio observations can and do play a crucial role, due to the long lifetime of the afterglow in this regime. This was the case for four out of five wide-angle jets identified in Table 1. One notable example is GRB 970508 where a jet model[36] of the radio data was found to be consistent with an analysis of the optical light curves.[10]

The Luminosities and Energies of GRB Central Engines

In Figure 2 we plot the measured fluence versus the inferred inverse beaming factor. There appears to be a correlation in the sense that the bursts with the largest fluence have the narrowest opening angles. This trend was noted earlier[11] albeit based on a few afterglows. The correlation is improved when the fluences are all scaled to the same redshift (unity), which effectively renders it to a correlation between $E_{\rm iso}(\gamma)$ and f_b^{-1}. The physical meaning of this trend is better appreciated from Figure 3 where we find that E_γ, the true energy released in gamma rays, is clustered around 5×10^{50} erg, with a 1σ multiplicative factor of only two.

Figures 2 and 3 suggest the following simple scenario: the central engines of GRBs produce approximately a similar amount of energy, and a significant part, about 10^{51} erg, escapes as gamma-rays (Figure 3). However, for reasons not presently understood, there exists a wide range of jet opening angles. If so, GRBs with the narrowest opening angles would be brighter and consequently produce the correlation seen in Figure 2.

The narrowness of the E_γ distribution is surprising and has several immediate implications. While it is not unreasonable to expect that the central engines produce a similar amount of energy, E_0, in each explosion, there is little reason to expect that they will produce similar gamma-ray outputs. Since the true total energy $E_0 \equiv E_\gamma/\eta_\gamma \propto n^{1/4}\eta_\gamma^{-3/4}$ (this follows from Equation 1), the narrowness in the distribution of E_γ places restrictions on the dispersion of n and η_γ.

If η_γ is high (close to unity) then a small dispersion in η_γ is naturally assured. Indeed, a number of recent papers[37–39] have argued that internal shocks under certain conditions are very efficient at producing gamma rays ($\eta_\gamma \gtrsim 0.2$). Furthermore, Guetta et al.[38] argue that the very conditions that are needed to make internal shocks efficient (a large dispersion in the distribution of the ejecta's Lorentz factors) also produce the characteristic clustering of spectral break energies of GRBs in the range 0.1–1 MeV.

Given a distribution in E_γ with a full width of a factor of four (see Figure 3), the dispersion in n ($\propto E_\gamma^4$) has to be less than two orders of magnitude. At first this may seem to be a weak constraint on the possible progenitors. However, the progenitors discussed to date lie either in intergalactic space or the halos of galaxies (ns-ns coalescence, $n \sim 10^{-6}$ cm^{-3} and $n \sim 10^{-4}$ cm^{-3}) or in a typical disk interstellar medium (ISM) or dense ISM (collapsar; $n \sim 1$ cm^{-3} and $n \sim 10^2$ cm^{-3}, respectively). Therefore our results limit the diversity of GRB environments, and specifically requires that the long-duration class of GRB events happen in only one of these environments. Furthermore, we note that winds of massive stars would produce a density of a few atoms cm^{-3} for $t_j \gtrsim 1$ d. In scenarios where there are two types of GRBs,[40] the ones that do not go off in stellar-wind-stratified media must reside within the disk of their host galaxy rather than in galaxy halos or the intergalactic medium. Indeed, the distribution of GRBs within their host galaxies is consistent with a disk population.[41] Likewise, broad-band modeling of GRB afterglows[5,24,36] give estimates of gas densities consistent with disks, justifying our normalization of n in Equation 1. We conclude that the progenitors of long duration GRBs likely come from one type of progenitor.

Finally, the narrowness of the E_γ distribution requires that the brightness of the γ-ray beam be roughly uniform from the center to the edge. This is contrary to models[42] in which large intensity variations within the conical blast wave are invoked in order to explain the wide dispersion of peak luminosities. We find that most of the dispersion in the luminosity is due to the diversity in opening angles.

The mean value of E_γ is 5×10^{50} erg (Figure 3). If we accept the conclusions of Guetta et al.[38] (see above), then $\eta_\gamma \sim 0.2$ and we then derive $E_0 \sim 3 \times 10^{51}$ erg. Of course, E_0 is sensitive, in addition to the adopted value of η_γ, to the overall scaling, i.e., the numerical coefficient of Equation 1. For example, the estimate of Rhoads,[10] based on a different assumption for the sideways expansion speed, has a coefficient smaller by a factor of six than our Equation 1.

Fortunately, GRB 970508 allows us to directly determine the energy scale. The radio afterglow of this GRB lasted long enough (400 d) that the blast wave was non-relativistic, thereby allowing determination of the total energy[36] independent of relativistic beaming. Table 1 shows that this burst has one of the lowest energies, although it is only 1σ away from the mean (if the energy distribution is assumed to be log normal). The agreement between these two entirely different approaches is remarkably good and gives some support to our choice of the numerical coefficient and normalization of Equation 1.

Freedman & Waxman[12] and Kumar[43] have suggested an elegant way to estimate the energy in the afterglow phase based on X-ray observations. This method yields the $\epsilon_e \varepsilon_a$ where ε_a is the energy of the blast wave per steradian and ϵ_e is the fraction of energy in the shocked electrons. This estimate is independent of the ambient density. If ϵ_e is high and relatively constant (analogous to the situation with η_γ) then E_0 can be estimated provided f_b is known. It is of interest to note that the ratio $\varepsilon_a/E_{\rm iso}(\gamma)$ is nearly constant,[12] suggesting that likely both ϵ_e and η_γ are narrowly distributed.

Applying our determinations of f_b to the sample of ref. 12 (a total of six common GRBs) we obtain $E_a = (2.7 \pm 1.4) \times 10^{50}$ erg. Within the limitations of the small sample, the distribution appears to be clustered and the results are in agreement with our findings (Figure 3). The principal advantage of our method is that the events are always identified in the γ-ray band, whereas X-ray observations are available for only a minority of cases. Furthermore, the X-ray afterglow technique ignores the effects of inverse Compton scattering effects,[44] and is therefore sensitive to the poorly known strengths of magnetic fields in strong shocks.

GRBs and SNe

Above we find that the mean total energy of GRBs is $E_0 \sim 3 \times 10^{51}$ erg. This energy is only slightly larger than the typical 10^{51} erg of electromagnetic and kinetic energy yield of ordinary supernovae (Ia, Ibc, II). This reduced energy budget raises the possibility that GRBs are the result of the formation of neutron stars,[45] albeit with special properties,[46] and does not necessarily require black holes. The mystery about GRBs is no longer in understanding their supposedly extraordinary energy budget but in explaining why the ejecta of GRBs have such a high Lorentz factor.

We note however that there are at least two possible exceptions to the tight clustering of jet energy. *(1)* If SN 1998bw is associated with a GRB[47,48] then $E_{\rm iso}(\gamma) \sim 7 \times 10^{47}$ erg. However, Kulkarni et al.[48] have argued that the extraordinarily bright radio emission from this SN requires $\gtrsim 10^{50}$ erg of the explosion energy to be in the form of mildly relativistic ejecta ($\Gamma \sim$ few). *(2)* Bloom et al.[49] identify the late time red bump in the rapidly decaying event GRB 980326 ($t_j < 0.55$ d; ref. 27) with an underlying SN. If so, the inferred redshift $z \sim 1$ and $E_\gamma < 7 \times 10^{49}$ erg. Unfortunately, the radio observations are not sensitive enough to place meaningful constraints on the amount of energy in mildly relativistic ejecta. In both cases, the true energy release could be closer to E_0 but this energy could be primarily in mildly relativistic ejecta. Careful observations (especially X-ray and radio) of SNe may uncover significant numbers of such "failed" GRBs.

Beaming Fraction and the GRB Rate

Since conical fireballs are visible to only a fraction, f_b, of observers, the true GRB rate, $R_t = \langle f_b^{-1} \rangle R_{\rm obs}$, where $R_{\rm obs}$ is the observed GRB rate and $\langle f_b^{-1} \rangle$ is the harmonic mean of the beaming fractions. We find $\langle f_b^{-1} \rangle \sim 500$ (see caption to Figure 1). The formal uncertainty in this estimate is only 16% but systematic uncertainties related our choice of the numerical coefficient and normalization of Equation 1. make this estimate accurate to a factor of two.

Estimates[50–52] of the local *observed* rate of GRBs give values of $R_{\rm obs}(z=0)$ ranging from 0.2 to 0.7 Gpc^{-3} yr^{-1}. The rate is uncertain because it is not known how the GRB rate evolves with redshift. We adopt a value $R_{\rm obs}(z=0) = 0.5$ Gpc^{-3} yr^{-1} as in Ref. 51. The true rate is $R_t(z=0) \sim 250$ Gpc^{-3} yr^{-1}, which should be compared with the estimated rate[53] of neutron star coalescence, $R_c(z=0) \sim 80$ Gpc^{-3} yr^{-1} and the estimated rate[53] of type Ibc SN, $R_{\rm Ibc} \sim 6 \times 10^4$ Gpc^{-3} yr^{-1}. Clearly, the collapsar scenario is capable of easily supplying a sufficient number of progenitors (including failed GRBs). Within the uncertainties of the estimates, the coalescence scenario is also (barely) capable of providing sufficient progenitors.

Assumptions, Uncertainties and Caveats

Our derivation of the jet opening angle is based on Equation 1 which makes two implicit assumptions. First, we assume that GRBs explode in a constant density medium and that any sharp break in the afterglow ($\Delta\alpha \gtrsim 0.75$) is attributed to a combination of the observer viewing beyond the edge of the conical jet and sideways expansion. Second, we assume that the conical blast wave maintains a fixed opening angle right from the GRB phase until Γ approaches θ_j^{-1}. The latter assumption imposes strict conditions on the working of the central engine. Specifically, the ejecta have to be approximately uniform across the entire opening angle in the gamma-ray phase and the bulk of the explosive energy in the afterglow phase must have a single bulk Lorentz factor.

The origin of the observed break is currently a matter of considerable theoretical debate.[54–56] The uncertainty is driven by the as yet unclear hydrodynamics of sideways expansion. Some authors[54,57] argue that transition is very smooth, and is completed in one decade of the break time for a constant density circumburst medium but takes two decades for the $n(r) \propto r^{-2}$ circumburst medium. Others[11] argue that several uncertainties in these calculations make this conclusion premature.

Furthermore, the analysis of the afterglow lightcurves does not yield ϕ, the angle between the line of sight to the observer and the principal axis of the jet. In general one may expect some dependence of t_j on ϕ and thus E_γ distribution should broaden even if E_0, η_γ and n were constants.

However, the narrowness of the E_γ distribution shown in Figure 3 provides empirical support for our assumptions. Furthermore, as noted earlier, where high quality observations are available (e.g., GRB 990510 and GRB 000301C) the breaks are found to be quite sharp and the inferred ambient density is ~ 1 cm^{-3}.

Finally, several other mechanisms have been proposed to produce steep declines in the afterglow light curves: *(i)* a sudden drop in the external density,[55] *(ii)* transition from relativistic to non-relativistic regime[58] due to expansion in a dense circumburst medium, and *(iii)* a break in the power-law distribution of radiating electrons.[59] These models have not been systematically compared against well studied afterglows and thus remain at a level of suggestions. Model *(ii)* can be rejected because the expected centimeter wave attenuation due to free-free absorption is not seen. Model *(iii)* is unable[59] to explain the broad-band achromatic breaks and will therefore fail to account for the early time low frequency emission. We conclude that at this stage the simple jet model which we have adopted provides a consistent and adequate description of the observations.

Our understanding of gamma-ray bursts has increased dramatically over the past four years. For nearly three decades these objects were considered so enigmatic that expectations of their distance ranged from local to cosmological scales. In the BATSE era, prior to the discovery of the afterglow phenomenon, the standard assumption was that GRBs possessed fixed peak luminosities. As more and more redshifts were obtained, the isotropic equivalent energy record increased, eventually reaching the rest mass energy of neutron stars. The standard candle hypothesis was consequently abandoned. It is remarkable that with a more detailed understanding of the afterglow we are able to infer the energy release in these bursts and find that GRBs are "standard candles" in some sense.

We have deduced the distribution of the opening angles of GRB jets and empirically uncovered a key clue, namely the total energy release and its approximate constancy, but we are still left with three significant mysteries. First, we do not know what physical mechanism results in such a wide variation in the opening angles of the jets. Second, the similarity of the energy release in GRBs and ordinary supernovae is puzzling. This coincidence is all the more remarkable considering the diversity of the progenitors and likely differing collapse mechanisms in these various classes of explosions. Third, we do not understand why in GRBs, the explosion energy couples only to $10^{-5}\,M_\odot$ of the exploding star and thereby produce ejecta with high Lorentz factor. Fortunately, new missions (HETE-2 and SWIFT) with their vastly increased GRB localization rates will provide empirical data which may help solve these mysteries.

Received 21 February 2001; Accepted .

1. Piran, T. Gamma-ray bursts - a puzzle being resolved. *Phys. Rep.* **333**, 529–553 (2000).

2. Sari, R., Piran, T. & Narayan, R. Spectra and Light Curves of Gamma-Ray Burst Afterglows. *Astrophys. J.* **497**, L17 (1998).

3. Waxman, E. Gamma-Ray Burst Afterglow: Confirming the Cosmological Fireball Model. *Astrophys. J.* **489**, L33–L36 (1997).

4. Galama, T. J., Wijers, R. A. M. J., Bremer, M., Groot, P. J., Strom, R. G., Kouveliotou, C. & Van Paradijs, J. The Radio-to-X-Ray Spectrum of GRB 970508 on 1997 May 21.0 UT. *Astrophys. J.* **500**, L97–L100 (1998).

5. Berger, E., Sari, R., Frail, D. A., Kulkarni, S. R., Bertoldi, F., Peck, A. B., Menten, K. M., Shepherd, D. S., Moriarty-Schieven, G. H., Pooley, G., Bloom, J. S., Diercks, A., Galama, T. J. & Hurley, K. A Jet Model for the Afterglow Emission from GRB 000301C. *Astrophys. J.* **545**, 56–62 December 2000.

6. Frontera, F., Amati, L., Costa, E., Muller, J. M., Pian, E., Piro, L., Soffitta, P., Tavani, M., Castro-Tirado, A., Dal Fiume, D., Feroci, M., Heise, J., Masetti, N., Nicastro, L., Orlandini, M., Palazzi, E. & Sari, R. Prompt and Delayed Emission Properties of Gamma-Ray Bursts Observed with BeppoSAX. *Astrophys. J. Supp. Series* **127**, 59–78 (2000).

7. Rhoads, J. E. How to Tell a Jet from a Balloon: A Proposed Test for Beaming in Gamma-Ray Bursts. *Astrophys. J.* **487**, L1–L4 (1997).

8. Waxman, E., Kulkarni, S. R. & Frail, D. A. Implications of the Radio Afterglow from the Gamma-Ray Burst of 1997 May 8. *Astrophys. J.* **497**, 288–293 (1998).

9. Panaitescu, A., Meszaros, P. & Rees, M. J. Multiwavelength Afterglows in Gamma-Ray Bursts: Refreshed Shock and Jet Effects. *Astrophys. J.* **503**, 314–324 (1998).

10. Rhoads, J. E. The Dynamics and Light Curves of Beamed Gamma-Ray Burst Afterglows. *Astrophys. J.* **525**, 737–749 (1999).

11. Sari, R., Piran, T. & Halpern, J. P. Jets in Gamma-Ray Bursts. *Astrophys. J.* **519**, L17–L20 (1999).

12. Freedman, D. L. & Waxman, E. On the Energy of Gamma-Ray Bursts. *Astrophys. J.* **547**, 922–928 (2001).

13. Gallant, Y. A., Achterberg, A. & Kirk, J. G. Particle acceleration at ultra-relativistic shocks. Gamma-ray burst afterglow spectra and UHECRs. *Astr. Astrophys.* **138**, 549–550 (1999).

14. Kulkarni, S. R., Djorgovski, S. G., Odewahn, S. C., Bloom, J. S., Gal, R. R., Koresko, C. D., Harrison, F. A., Lubin, L. M., Armus, L., Sari, R., Illingworth, G. D., Kelson, D. D., Magee, D. K., Van Dokkum, P. G., Frail, D. A., Mulchaey, J. S., Malkan, M. A., MCClean, I. S., Teplitz, H. I., Koerner, D., Kirkpatrick, D., Kobayashi, N., Yadigaroglu, I. A., Halpern, J., Piran, T., Goodrich, R. W., Chaffee, F. H., Feroci, M. & Costa, E. The Afterglow, Redshift, and Extreme Energetics of the Gamma-Ray Burst of 23 January 1999. *Nature* **398**, 389–394 (1999).

15. Fruchter, A., Thorsett, S. & Wijers, R. GCN notice 712 (2000).

16. Kulkarni, S. R., Frail, D. A., Sari, R., Moriarty-Schieven, G. H., Shepherd, D. S., Udomprasert, P., Readhead, A. C. S., Bloom, J. S., Feroci, M. & Costa, E. Discovery of a Radio Flare from GRB 990123. *Astrophys. J.* **522**, L97–L100 (1999).

17. Stanek, K. Z., Garnavich, P. M., Kaluzny, J., Pych, W. & Thompson, I. BVRI Observations of the Optical Afterglow of GRB 990510. *Astrophys. J.* **522**, L39–L42 (1999).

18. Harrison, F. A., Bloom, J. S., Frail, D. A., Sari, R., Kulkarni, S. R., Djorgovski, S. G., Axelrod, T., Mould, J., Schmidt, B. P., Wieringa, M. H., Wark, R. M., Subrahmanyan, R., McConnell, D., McCarthy, P. J., Schaefer, B. E., McMahon, R. G., Markze, R. O., Firth, E., Soffitta, P. & Amati, L. Optical and Radio Observations of the Afterglow from GRB 990510: Evidence for a Jet. *Astrophys. J.* **523**, L121–L124 (1999).

19. Pian, E., Soffitta, P., Alessi, A., Amati, L., Costa, E., Frontera, F., Fruchter, A., Masetti, N., Palazzi, E., Panaitescu, A. & Kumar, P. A&A (Let) submitted, astro-ph/0012107 (2000).

20. Covino, S., Lazzati, D., Ghisellini, G., Saracco, P., Campana, S., Chincarini, G., di Serego, S., Cimatti, A., Vanzi, L., Pasquini, L., Haardt, F., Israel, G. L., Stella, L. & Vietri, M. GRB 990510: linearly polarized radiation from a fireball. *Astr. Astrophys.* **348**, L1–L4 (1999).

21. Wijers, R. A. M. J., Vreeswijk, P. M., Galama, T. J., Rol, E., Van Paradijs, J., Kouveliotou, C., Giblin, T., Masetti, N., Palazzi, E., Pian, E., Frontera, F., Nicastro, L., Falomo, R., Soffitta, P. & Piro, L. Detection of Polarization in the Afterglow of GRB 990510 with the ESO Very Large Telescope. *Astrophys. J.* **523**, L33–L36 (1999).

22. Ghisellini, G. & Lazzati, D. Polarization light curves and position angle variation of beamed gamma-ray bursts. *Mon. Not. R. astr. Soc.* **309**, L7–L11 (1999).

23. Sari, R. Linear Polarization and Proper Motion in the Afterglow of Beamed Gamma-Ray Bursts. *Astrophys. J.* **524**, L43–L46 (1999).

24. Panaitescu, A. & Kumar, P. submitted to the ApJ, astro-ph/0010257 (2000).

25. Masetti, N., Bartolini, C., Bernabei, S., Guarnieri, A., Palazzi, E., Pian, E., Piccioni, A., Castro-Tirado, A. J., Castro Cerón, J. M., Verdes-Montenegro, L., Sagar, R., Mohan, V., Pandey, A. K., Pandey, S. B., Bock, H., Greiner, J., Benetti, S., Wijers, R. A. M. J., Beskin, G. M. & Gorosabel, J. Unusually rapid variability of the GRB000301C optical afterglow. *Astr. Astrophys.* **359**, L23–L26 (2000).

26. Garnavich, P. M., Loeb, A. & Stanek, K. Z. Resolving Gamma-Ray Burst 000301C with a Gravitational Microlens. *Astrophys. J.* **544**, L11–L15 (2000).

27. Groot, P. J., Galama, T. J., Vreeswijk, P. M., Wijers, R. A. M. J., Pian, E., Palazzi, E., Van Paradijs, J., Kouveliotou, C., In 't Zand, J. J. M., Heise, J., Robinson, C., Tanvir, N., Lidman, C., Tinney, C., Keane, M., Briggs, M., Hurley, K., Gonzalez, J.-F., Hall, P., Smith, M. G., Covarrubias, R., Jonker, P., Casares, J., Frontera, F., Feroci, M., Piro, L., Costa, E., Smith, R., Jones, B., Windridge, D., Bland-Hawthorn, J., Veilleux, S., Garcia, M., Brown, W. R., Stanek, K. Z., Castro-Tirado, A. J., Gorosabel, J., Greiner, J., Jaeger, K., Bohm, A. B. & Fricke, K. J. The Rapid Decay of the Optical Emission from GRB 980326 and Its Possible Implications. *Astrophys. J.* **502**, L123–+ August 1998.

28. Jaunsen, A. O., Hjorth, J., Bjornsson, G., Andersen, M. I., Pedersen, H., Kjernsmo, K., Korhonen, H., Sorensen, P. M. & Palazzi, E. ApJ, in press. astro-ph/0007320 (2000).

29. Stratta, G. et al. in *Gamma Ray Bursts: 5th Huntsville Symposium* (eds R. M. Kippen, R. S. M. & Fishman, G. J.) 375–379 (AIP, Woodbury, New York, 2000).

30. Costa, E. in *Gamma Ray Bursts: 5th Huntsville Symposium* (eds R. M. Kippen, R. S. M. & Fishman, G. J.) 365–374 (AIP, Woodbury, New York, 2000).

31. Feroci, M., Antonelli, L. A., Guainazzi, M., Muller, J. M., Costa, E., Piro, L., In 't Zand, J. J. M., Frontera, F., Dal Fiume, D., Nicastro, L., Orlandini, M., Palazzi, E., Zavattini, G., Giommi, P., Parmar, A. N., Owens, A., Castro-Tirado, A. J., Maccarone, M. C. & Butler, R. C. BeppoSAX follow-up search for the X-ray afterglow of GRB970111. *Astr. Astrophys.* **332**, L29–L33 (1998).

32. Perna, R. & Loeb, A. Constraining the Beaming of Gamma-Ray Bursts with Radio Surveys. *Astrophys. J.* **509**, L85–L88 (1998).

33. Grindlay, J. E. Fast X-Ray Transients and Gamma-Ray Bursts: Constraints on Beaming. *Astrophys. J.* **510**, 710–714 (1999).

34. Halpern, J. P., Uglesich, R., Mirabal, N., Kassin, S., Thorstensen, J., Keel, W. C., Diercks, A., Bloom, J. S., Harrison, F., Mattox, J. & Eracleous, M. GRB 991216 Joins the Jet Set: Discovery and Monitoring of Its Optical Afterglow. *Astrophys. J.* **543**, 697–703 (2000).

35. Berger, E. et al. ApJ, submitted (2001).

36. Frail, D. A., Waxman, E. & Kulkarni, S. R. A 450 day light curve of the radio afterglow of GRB 970508: fireball calorimetry. *Astrophys. J.* **537**, 191–204 (2000).

37. Beloborodov, A. M. On the efficiency of internal shocks in gamma-ray bursts. *Astrophys. J.* **539**, L25–L28 (2000).

38. Guetta, D., Spada, M. & Waxman, E. Submitted to ApJ; astro-ph/0011170 (2001).

39. Kobayashi, S. & Sari, R. ApJ, in press; astro-ph/0101006 (2001).

40. Chevalier, R. A. & Li, Z. Wind Interaction Models for Gamma-Ray Burst Afterglows: The Case for Two Types of Progenitors. *Astrophys. J.* **536**, 195–212 (2000).

41. Bloom, J. S., Kulkarni, S. R. & Djorgovski, S. G. submitted to AJ. astro-ph/0010176 (2000).

42. Kumar, P. & Piran, T. Energetics and Luminosity Function of Gamma-Ray Bursts. *Astrophys. J.* **535**, 152–157 (2000).

43. Kumar, P. The Distribution of Burst Energy and Shock Parameters for Gamma-Ray Bursts. *Astrophys. J.* **538**, L125–L128 (2000).

44. Sari, R. & Esin, A. A. ApJ submitted, astro-ph/0005253 (2000).

45. Wheeler, J. C., Yi, I., Höflich, P. & Wang, L. Asymmetric Supernovae, Pulsars, Magnetars, and Gamma-Ray Bursts. *Astrophys. J.* **537**, 810–823 (2000).

46. Usov, V. V. Millisecond pulsars with extremely strong magnetic fields as a cosmological source of gamma-ray bursts. *Nature* **357**, 472–474 (1992).

47. Galama, T. J., Vreeswijk, P. M., Van Paradijs, J., Kouveliotou, C., Augusteijn, T., Bohnhardt, H., Brewer, J. P., Doublier, V., Gonzalez, J.-F., Leibundgut, B., Lidman, C., Hainaut, O. R., Patat, F., Heise, J., In 't Zand, J., Hurley, K., Groot, P. J., Strom, R. G., Mazzali, P. A., Iwamoto, K., Nomoto, K., Umeda, H., Nakamura, T., Young, T. R., Suzuki, T., Shigeyama, T., Koshut, T., Kippen, M., Robinson, C., De Wildt, P., Wijers, R. A. M. J., Tanvir, N., Greiner, J., Pian, E., Palazzi, E., Frontera, F., Masetti, N., Nicastro, L., Feroci, M., Costa, E., Piro, L., Peterson, B. A., Tinney, C., Boyle, B.,

Cannon, R., Stathakis, R., Sadler, E., Begam, M. C. & Ianna, P. An unusual supernova in the error box of the gamma-ray burst of 25 April 1998. *Nature* **395**, 670–672 (1998).

48. Kulkarni, S. R., Frail, D. A., Wieringa, M. H., Ekers, R. D., Sadler, E. M., Wark, R. M., Higdon, J. L., Phinney, E. S. & Bloom, J. S. Radio Emission from the Unusual Supernova 1998bw and its Association with the Gamma-Ray Burst of 25 April 1998. *Nature* **395**, 663–669 (1998).

49. Bloom, J. S. et al. The unusual afterglow of GRB 980326: evidence for the gamma-ray burst/supernova connection. *Nature* **401**, 453–456 (1999).

50. Wijers, R. A. M. J., Bloom, J. S., Bagla, J. & Natarajan, P. Gamma-Ray Bursts from Stellar Remnants: Probing the Universe at High Redshift. *Mon. Not. R. astr. Soc.* **294**, L17–L21 (1998).

51. Schmidt, M. ApJ in press, astro-ph/0101163 (2001).

52. Kommers, J. M., Lewin, W. H. G., Kouveliotou, C., van Paradijs, J., Pendleton, G. N., Meegan, C. A. & Fishman, G. J. The Intensity Distribution of Faint Gamma-Ray Bursts Detected with BATSE. *Astrophys. J.* **533**, 696–709 (2000).

53. Phinney, E. S. The rate of neutron star binary mergers in the universe - Minimal predictions for gravity wave detectors. *Astrophys. J.* **380**, L17–L21 (1991).

54. Panaitescu, A. & Mészáros, P. Dynamical Evolution, Light Curves, and Spectra of Spherical and Collimated Gamma-Ray Burst Remnants. *Astrophys. J.* **526**, 707–715 (1999).

55. Kumar, P. & Panaitescu, A. Afterglow Emission from Naked Gamma-Ray Bursts. *Astrophys. J.* **541**, L51–L54 (2000).

56. Wei, D. M. & Lu, T. Can the Jet Steepen the Light Curves of Gamma-Ray Burst Afterglows? *Astrophys. J.* **541**, 203–206 (2000).

57. Panaitescu, A. & Kumar, P. Analytic Light Curves of Gamma-Ray Burst Afterglows: Homogeneous versus Wind External Media. *Astrophys. J.* **543**, 66–76 (2000).

58. Wang, X. Y., Dai, Z. G. & Lu, T. A possible explanation for the radio afterglow of GRB 980519: the dense medium effect. *Mon. Not. R. astr. Soc.* **317**, 170–174 (2000).

59. Li, Z.-Y. & Chevalier, R. A. submitted to ApJ, astro-ph/0010288 (2000).

60. Reichart, D. E. ApJ in press, astro-ph/9912368 (2001).

61. Reichart, D. E., Lamb, D. Q., Fenimore, E. E., Ramirez-Ruiz, E., Cline, T. L. & Hurley, K. ApJ in press, astro-ph/0004302 (2001).

62. Djorgovski, S. G., Frail, D. A., Kulkarni, S. R., Bloom, J., Odewahn, S. C. & Diercks, A. ApJ (Let) submitted (2000).

63. Kulkarni, S. R., Djorgoski, S. G., Ramaprakash, A. N., Goodrich, R., Bloom, J. S., Adelberger, K. L., Kundic, T., Lubin, L., Frail, D. A., Frontera, F., Feroci, M., Nicastro, L., Barth, A. J., Davis, M., Filippenko, A. V. & Newman, J. Identification of a host galaxy at redshift z = 3.42 for the gamma-ray burst of 14 December 1997. *Nature* **393**, 35–39 (1998).

64. Halpern, J. P. & Fesen, R. GCN notice 134 (1998).

65. Berger, E. et al. in preparation (2000).

66. Masetti, N., Palazzi, E., Pian, E., Hunt, L. K., Méndez, M., Frontera, F., Amati, L., Vreeswijk, P. M., Rol, E., Galama, T. J., van Paradijs, J., Antonelli, L. A., Nicastro, L., Feroci, M., Marconi, G., Piro, L., Costa, E., Kouveliotou, C., Castro-Tirado, A. J., Falomo, R., Augusteijn, T., Böhnhardt, H., Lidman, C., Vanzi, L., Merrill, K. M., Kaminsky, C. D., van der Klis, M., Heemskerk, M. H. M., van der Hooft, F., Kuulkers, E., Pedersen, H. & Benetti, S. Near-infrared detection and optical follow-up of the GRB990705 afterglow. *Astr. Astrophys.* **354**, 473–479 (2000).

67. Fruchter, A., Vreeswijk, P., Hook, R. & Pian, E. GCN notice 752 (2000).

68. Jensen, B. L., Hjorth, J., Pedersen, H., Kristen, H. E., Tomassi, L., Pian, E. & Hurley, K. GCN notice 454 (1999).

69. Andersen, M. I., Hjorth, J., Pedersen, H., Jensen, B. L., Hunt, L. K., Gorosabel, J., Møller, P., Fynbo, J., Kippen, R. M., Thomsen, B., Olsen, L. F., Christensen, L., Vestergaard, M., Masetti, N., Palazzi, E., Hurley, K., Cline, T., Kaper, L. & Jaunsen, A. O. VLT identification of the optical afterglow of the gamma-ray burst GRB 000131 at z=4.50. *Astr. Astrophys.* **364**, L54–L61 (2000).

70. Price, P. A., Harrison, F. A., Galama, T. J., Reichart, D. E., Axelrod, T. S., Bloom, J. S., Busche, J., Cline, T., Diercks, A., Djorgovski, S. G., Frail, D. A., Gal-Yam, A., Halpern, J., Holtzman, J. A., Hunt, M., Hurley, K., Jacoby, B., Kimble, R., Kulkarni, S. R., Mirabal, N., Morrison, G., Ofek, E., Pevunova, O., Sari, R., Schmidt, B. P., Turnshek, D. & Yost, S. ApJ Let., submitted; astro-ph/0012303 (2000).

71. Bloom, J. S. et al. AJ, submitted (2000).

Acknowledgements

Our research is supported by NASA and NSF. JSB thanks the Fannie & John Hertz Foundation for their generous support, AD holds a Millikan Postdoctoral Fellowship in Experimental Physics, TJG holds a Fairchild Foundation Postdoctoral Fellowship in Observational Astronomy, DER holds a Hubble Fellowship and RS holds a Fairchild Foundation Senior Fellowship in Theoretical Astrophysics. The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc. We thank the staff at the Keck and Palomar Observatoroes for their expert help during many observing runs. The W. M. Keck Observatory is operated by the California Association for Research in Astronomy, a scientific partnership among the California Institute of Technology, the University of California and the National Aeronautics and Space Administration. It was made possible by the generous financial support of the W. M. Keck Foundation.

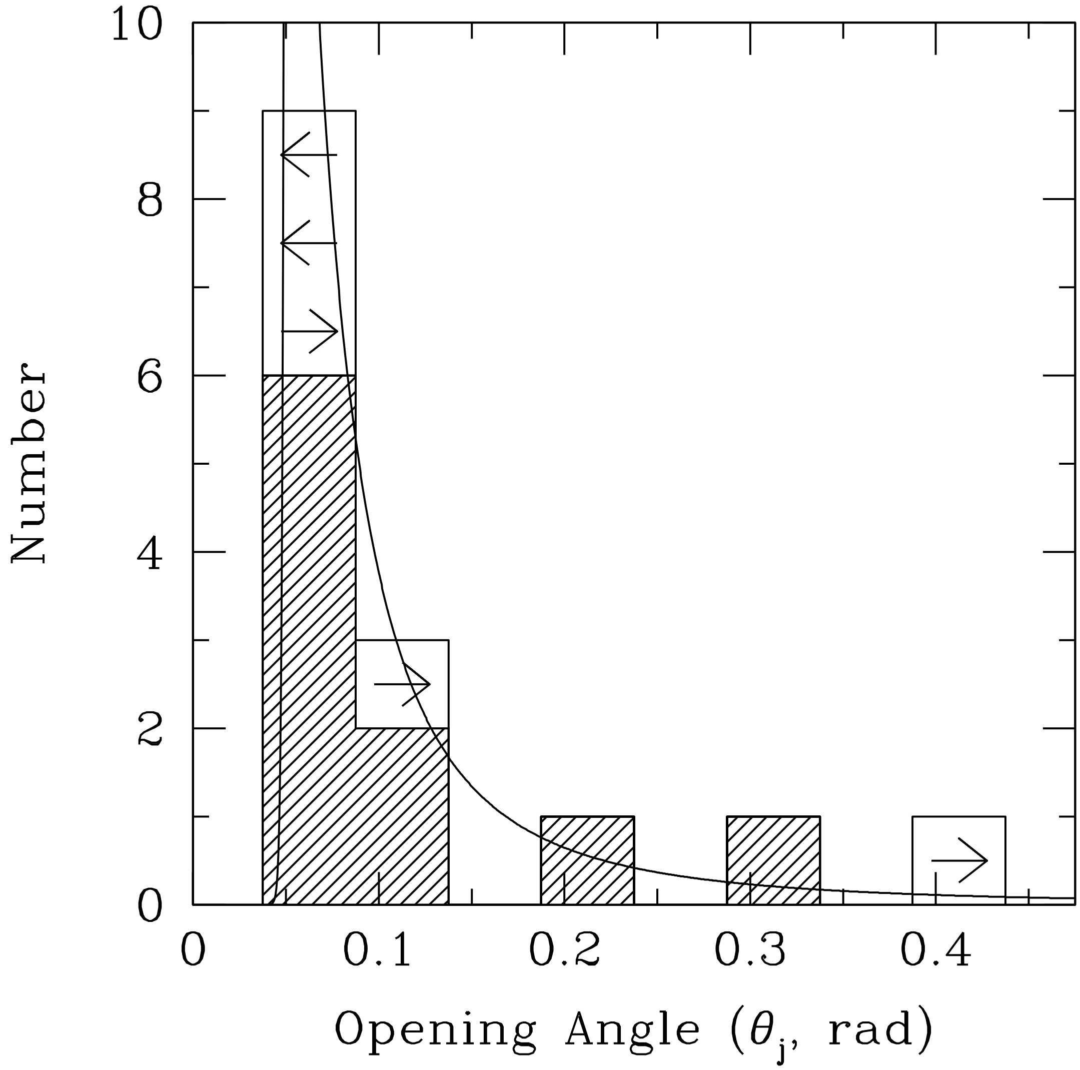

Figure 1. The observed distribution of jet opening angles along with a model fit (line). We assume that the observed differential distribution of beaming factors can be represented by two power laws: $p_{\rm obs}(f_b) = (f_b/f_0)^{\alpha+1}$ for $f_b < f_0$ and $p_{\rm obs}(f_b) = (f_b/f_0)^{\beta+1}$ for $f_b > f_0$. Since for every observed burst there are f_b^{-1} that are not observed, the true distribution is $p_{\rm true}(f_b) = f_b^{-1} p_{\rm obs}(f_b)$. Fitting to the data, we find the following: α is poorly constrained; $\beta = -2.77^{+0.24}_{-0.30}$; $\log f_0 = -2.91^{+0.07}_{-0.06}$. Thus, the true differential probability distribution (under the small angle approximation, $f_b \propto \theta_j^2$) is given by $p_{\rm true}(\theta_j) \propto \theta_j^{-4.54}$ with the observed distribution being $p_{\rm obs} \propto \theta_j^{-2.54}$. The distribution $p_{\rm true}(f_b)$ allows us to estimate the true correction factor, $\langle f_b^{-1} \rangle$ that has to be applied to the observed GRB rate in order to obtain the true GRB rate. We find $\langle f_b^{-1} \rangle = f_0^{-1}[(\beta - 1)/\beta] \sim 520 \pm 85$.

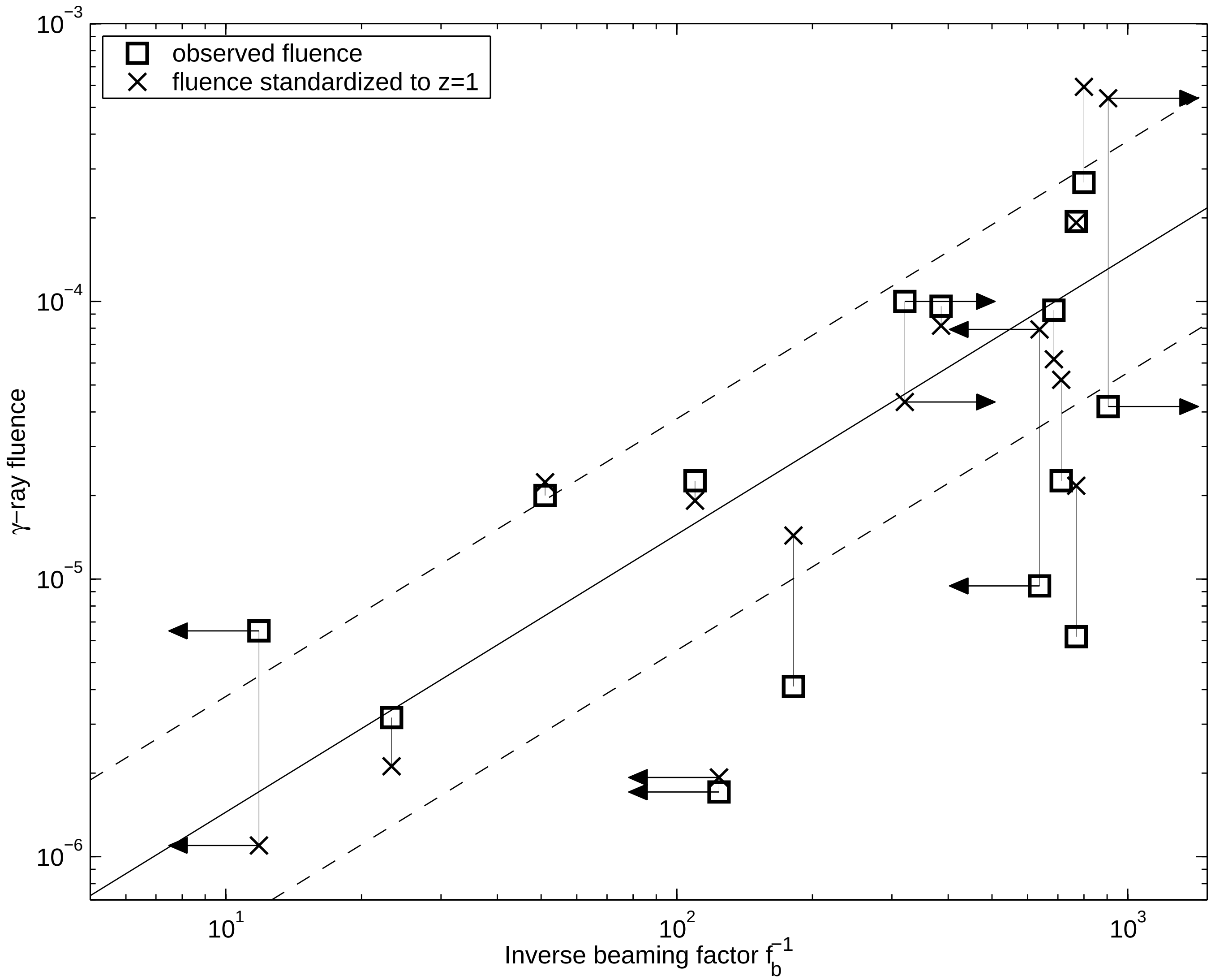

Figure 2. The gamma-ray fluence F_γ (in units of erg cm^{-2}) plotted as a function of the inverse beaming fraction f_b^{-1} (where $f_b = 1 - \cos\theta_j \cong \theta_j^2/2$, and θ_j is the opening angle of the jet). A correlation is apparent in the sense that GRBs that have narrower jet opening angles are brighter (high fluence) than those that do not. A linear fit to these data (open squares) gives a relatively large rms scatter of a factor of 3.3. The correlation is improved when the fluences are all scaled to the same unity redshift (crosses), thereby removing the distance dependence. The rms scatter (dashed lines) of these points around a linear fit (solid line) is reduced to only a factor of 2.3. This factor is marked by dashed lines around the linear fit. The wide variation in observed fluence, more than two orders of magnitude, appears to be mainly due to different beaming angles.

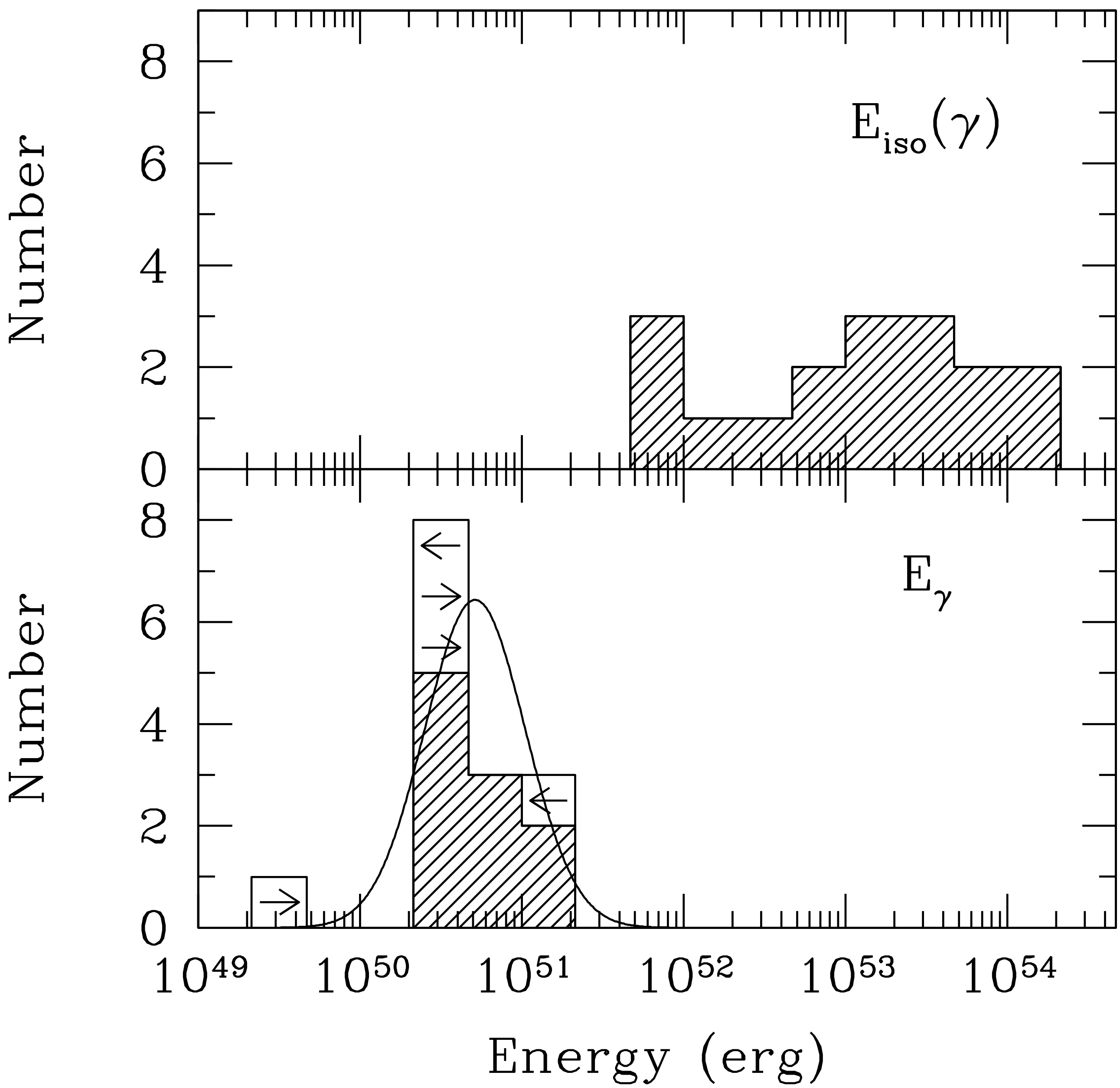

Figure 3. The distribution of the apparent isotropic γ-ray burst energy of GRBs with known redshifts (top) versus the geometry-corrected energy for those GRBs whose afterglows exhibit the signature of a non-isotropic outflow (bottom). The mean isotropic equivalent energy $\langle E_{iso}(\gamma)\rangle$ for 17 GRBs is 110×10^{51} erg with a 1-σ spreading of a multiplicative factor of 6.2. In estimating the mean geometry-corrected energy $\langle E_\gamma \rangle$ we applied the Bayesian inference formalism[60] and modified to handle datasets containing upper and lower limits.[61] Arrows are plotted for five GRBs to indicate upper or lower limits to the geometry-corrected energy. The value of $\langle \log E_\gamma \rangle$ is 50.71 ± 0.10 (1σ) or equivalently, the mean geometry-corrected energy $\langle E_\gamma \rangle$ for 15 GRBs is 0.5×10^{51} erg. The standard deviation in $\log E_\gamma$ is $0.31^{+0.09}_{-0.06}$, or a 1-σ spread corresponding to a multiplicative factor of 2.0.

GRB	F_γ	z	d_L	$E_{\rm iso}(\gamma)$	t_j	θ_j	E_γ	Refs.	Note
970228	11.0	0.695	1.4	22.4					N
970508	3.17	0.835	1.8	5.46	25	0.293	0.234	36	R
970828	96.0	0.958	2.1	220	2.2	0.072	0.575	62	X
971214	9.44	3.418	9.9	211	> 2.5	> 0.056	> 0.333	63	O
980613	1.71	1.096	2.5	5.67	> 3.1	> 0.127	> 0.045	64	O
980703	22.6	0.966	2.1	60.1	7.5	0.135	0.544	65	B
990123	268	1.600	3.9	1440	2.04	0.050	1.80	14	O
990506	194	1.30	3.0	854					N
990510	22.6	1.619	4.0	176	1.20	0.053	0.248	18	B
990705	93	0.84	1.8	270	$\sim$1	0.054	0.389	66	O
990712	6.5	0.433	0.8	5.27	> 47.7	> 0.411	> 0.445	67	O
991208	100	0.706	1.4	147	< 2.1	< 0.079	< 0.455	68	D
991216	194	1.02	2.3	535	1.2	0.051	0.695	34	O
000131	41.8	4.500	13.7	1160	< 3.5	< 0.047	< 1.30	69	D
000301C	4.1	2.034	5.3	46.4	5.5	0.105	0.256	5	B
000418	20.0	1.119	2.5	82.0	25	0.198	1.60	35	B
000926	6.2	2.037	5.3	297	1.45	0.051	0.379	70	O

Table 1. Jet Break Times and Energetics. The gamma-ray fluences (F_γ), given in units of 10^{-6} erg cm^{-3}, are from a diverse collection of instruments. The best determinations of energy fluence are from the *Burst and Transient Experiment* (BATSE) on the *Compton Gamma-Ray Observatory* (CGRO). Most of the GRBs (10), prior to the de-orbit of CGRO on 2000 May 26, are BATSE bursts. In these cases we used fits to BATSE data which were integrated over the energy range from 20 to 2000 keV. For the remainder of the events we used the fluence as determined from the Gamma-Ray Burst Monitor on the BeppoSAX satellite (40-700 keV), or fluences (25-1000 keV or 25-100 keV) from the Interplanetary Network of satellites (*Ulysses*, KONUS, and *NEAR*).[71] The luminosity distance (d_L) is given in units of 10^{28} cm. It was calculated from the observed redshift (z), and adopting cosmological parameters of H$_\circ$=65 km s^{-1} Mpc^{-1}, Ω_M=0.3, and $\Lambda_\circ$=0.7. Other realistic cosmologies were tried but they did not fundamentally change our conclusions. The isotropic γ-ray energies ($E_{\rm iso}(\gamma)$), given in units of 10^{51} erg, have been "k-corrected" such that all energy estimates are referenced to the same 20-2000 keV co-moving bandpass.[71] Although these order-of-unity corrections affect individual determinations of $E_{\rm iso}(\gamma)$, they do not affect our results derived from the sample as a whole. The jet break times (t_j), given in days, are taken from the literature. The notes and the references in the table indicate how t_j was determined. The strongest evidence for collimated outflows come from GRBs with achromatic breaks in their broad-band light curves (B). In most cases such multi-frequency datasets are not available, so there is a second class of events with breaks determined primarily from radio (R), optical (O), or X-ray (X) data. We include here a number of events for which no break was observed, yielding only lower limits of t_j. For some GRBs the steep decline of the light curve, indicating a jet geometry, is already fully manifest at the time of the first measurement. In these cases (D) we have only an upper limit on t_j. The final group of GRBs are those for which t_j cannot be determined (N), owing to complications in the light curve such as the presence of a supernova signature (i.e., GRB 970828), or the lack of sufficient data. The beaming-corrected gamma-ray energy (E_γ), given in units of 10^{51} erg, was calculated by applying the geometric correction factor f_b to $E_{\rm iso}(\gamma)$.